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## Measurements of Pollution in the Troposphere (MOPITT) validation exercises during summer 2004 field campaigns over North America

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[1] Measurements of carbon monoxide (CO) made as part of three aircraft experiments during the summer of 2004 over North America have been used for the continued validation of the CO retrievals from the Measurements of Pollution in the Troposphere (MOPITT) instrument on board the Terra satellite. Vertical profiles measured during the NASA INTEX-A campaign, designed to be coincident with MOPITT overpasses, as well as measurements made during the COBRA-2004 and MOZAIC experiments, provided valuable validation comparisons. On average, the MOPITT CO retrievals are biased slightly high for these North America locations. While the mean bias differs between the different aircraft experiments (e.g., 7.0 ppbv for MOZAIC to 18.4 ppbv for COBRA at 700 hPa), the standard deviations are quite large, so the results for the three data sets can be considered consistent. On average, it is estimated that MOPITT is 7–14% high at 700 hPa and ~3% high at 350 hPa. These results are consistent with the validation results for the Carr, Colorado, Harvard Forest, Massachusetts, and Poker Flats, Alaska, aircraft profiles for “phase 2” presented by Emmons et al. (2004) and are generally within the design criteria of 10% accuracy.

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### 1. Introduction

[2] The Measurement of Pollution in the Troposphere (MOPITT) instrument on board the Terra satellite has been making global measurements of the carbon monoxide (CO) distribution in the troposphere for over 6 years and continues to operate well. While instrument parameters and calibration factors remain stable, it is necessary to perform validation comparisons with independent measurements to show that the retrieved CO concentrations are accurate and remain stable over time within the range of uncertainty given by validation studies. Validation of the MOPITT CO retrievals for the years 2000–2002 was performed with a number of in situ measurements from aircraft [Emmons et al., 2004]. These results showed very good agreement between the MOPITT CO version 3 retrievals and the in situ measurements. The phase 1 retrievals (March 2000 to

May 2001) have a slight positive bias, with a global average of 4 ppbv at 700 hPa and 2 ppbv at 350 hPa. The bias is slightly lower for the phase 2 (since August 2001) retrievals (less than  $\pm 1$  ppbv at all altitudes).

[3] During the summer of 2004, several aircraft experiments were studying the atmospheric composition over North America, and consequently provided a set of in situ CO profile observations valuable for the validation of MOPITT CO retrievals. Among these was the NASA Intercontinental Chemical Transport Experiment (INTEX-A) [Singh et al., 2006], part of the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT), which focused on the transport of pollutants into and out of North America [Fehsenfeld et al., 2006]. The CO<sub>2</sub> Budget and Rectification Airborne (COBRA) study included aircraft sampling to link surface and tower measurements from terrestrial ecosystems to the regional scale, similar to the COBRA-NA study in 2000 [Gerbig et al., 2003]. The third set of data used in this study is from measurements made from commercial aircraft as part of the MOZAIC (Measurement of OZone, water vapour, carbon monoxide and nitrogen oxides by Airbus In-service airCRAFT) program. While MOZAIC makes measurements over much of the globe, only profiles over North America were used for this study focusing on the ICARTT campaign.

[4] The CO retrievals from MOPITT were used in flight planning during INTEX-A, providing large-scale context for the aircraft measurements. MOPITT CO has also been used to improve emission estimates of the Alaska and

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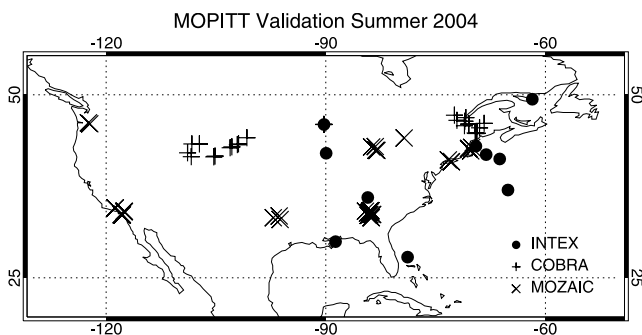
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**Figure 1.** Location of INTEX-A, COBRA-2004 and MOZAIC/ICARTT validation profiles.

Canada wildfires that burned during the summer of 2004 [Pfister *et al.*, 2005; Turquety *et al.*, 2007]. The validation of the MOPITT retrievals during this period is particularly critical for supporting those results, as well as other studies of the ICARTT measurements using MOPITT observations. This paper presents the validation of MOPITT CO retrievals using several aircraft data sets during the summer of 2004. The following section describes the in situ measurements, followed by a description of the validation results and discussion, and conclusions.

## 2. Aircraft Measurements

### 2.1. INTEX-A

[5] The NASA DC-8 sampled ten profiles during INTEX-A coincident with MOPITT overpasses. These were on 8, 15, 22, 25, and 31 July and 2, 6, 7, 11, and 13 August (flights 5, 8, 11, 12, 14–19), and their locations are shown in Figure 1. The profiles were sampled on spirals of 50–100 km radius between the surface and about 250 hPa. Since these DC-8 flights were designed to underfly Terra, the coincidence in time for these comparisons was generally within an hour.

[6] The majority of the in situ CO measurements from INTEX-A were made by the fast response tunable diode laser (TDL) instrument DACOM (Differential Absorption CO Measurement) [Sachse *et al.*, 1987]. The time response of the measurements is 1 s and their precision is 1% or 1 ppbv, whichever is greater. Measurement accuracy is closely tied to the accuracy of the reference gases obtained from the NOAA Earth System Research Laboratory (ESRL, formerly CMDL: Climate Monitoring and Diagnostics Laboratory). For the profile on 31 July, DACOM measurements were only available below 3 km because of instrument problems, thus CO measurements from the University of California-Irvine canister samples were used for the upper part of the profile. Comparison of the canister samples and DACOM where they were coincident show excellent agreement.

### 2.2. COBRA-2004

[7] The CO<sub>2</sub> Budget and Rectification Airborne (COBRA) study measured a large number of profiles from the University of Wyoming King Air over eastern Canada during 7 May to 16 June and 17 July to 14 August. CO was measured using the Vacuum-Ultraviolet (VUV) fluorescence technique, with a precision of 2 ppbv and accuracy of 3 ppbv for a sampling rate of 1 Hz [Gerbig *et al.*, 1996,

1999]. Calibrations were made with gas standards traceable to NOAA/ESRL.

[8] Profiles were fortuitously coincident with MOPITT overpasses on 21 occasions (locations shown in Figure 1). A few of the profiles were sampled as spirals of 15–30 km radius, however, most of the profiles were performed along the flight track, covering about 100 km, sampling between the surface and about 350 hPa.

### 2.3. MOZAIC

[9] The MOZAIC (Measurement of OZone, water vapor, carbon monoxide and nitrogen oxides by Airbus In-service airCraFt) program includes measurements of CO on several commercial aircraft. CO measurements were made with an improved infrared correlation instrument with a time resolution of 30 s, and a precision of  $\pm 5$  ppbv  $\pm 5\%$  [Nédélec *et al.*, 2003].

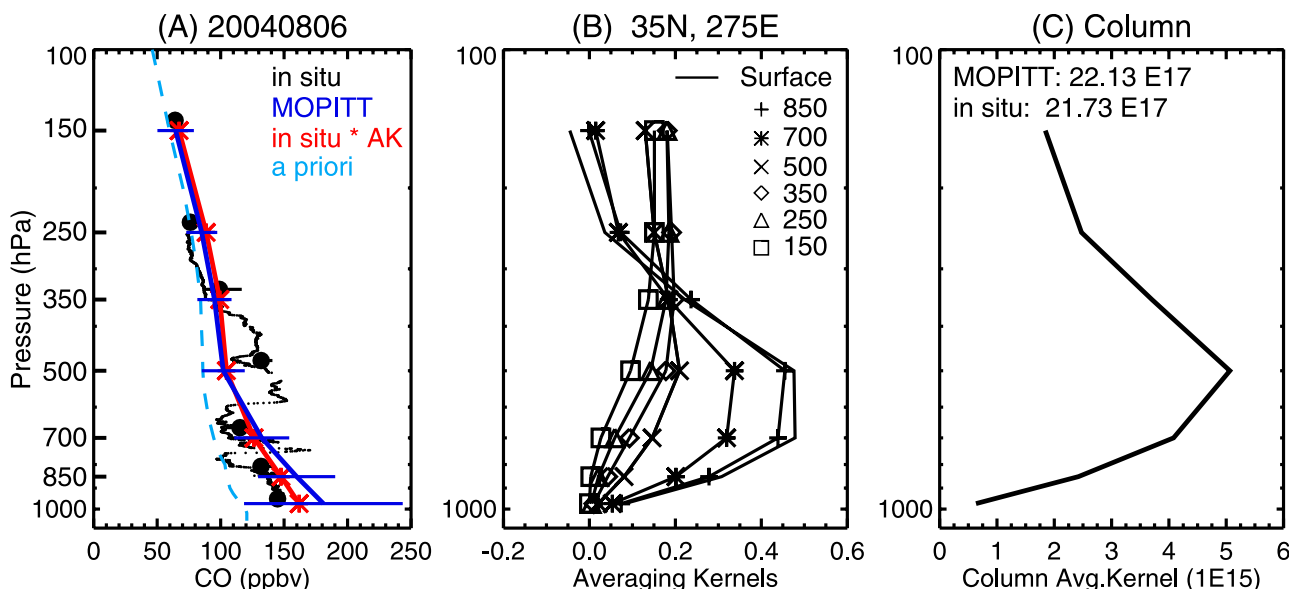
[10] Profiles of CO on descent to or ascent from several airports in North America happened to be coincident with MOPITT profiles on 32 occasions between 1 July and 16 August (17 at Atlanta, 4 at Los Angeles, 2 each at Boston, Dallas, Detroit and Seattle, and 1 each at Montreal, New York and Toronto). These “profiles” are actually sampled over 150–400 km in distance, between the surface and 300 hPa, so there can be significant differences in the CO distribution over those distances. However, the MOPITT measurements are relatively insensitive to the CO concentrations at the surface or in the upper troposphere, so the location of the MOZAIC measurements in the lower to middle troposphere is of primary concern for the validation. Therefore the mean latitude and longitude of the MOZAIC measurements between 800 and 500 hPa are used for matching with MOPITT overpasses. Thus the locations shown in Figure 1 are generally removed from the exact airport locations.

## 3. Validation Results and Discussion

[11] The MOPITT retrievals are based on the maximum a posteriori technique, incorporating a priori information about the CO profile and its covariance [Deeter *et al.*, 2003]. The MOPITT instrument and the retrieval algorithm used for this study are the same as the “phase 2” configuration of the version 3 retrievals [Emmons *et al.*, 2004]. As described by Emmons *et al.* [2004], the in situ profiles ( $x$ ) must be transformed with averaging kernels ( $A$ ) and the a priori CO profile ( $x_a$ ) to create a profile ( $x_{ret}$ ) appropriate to be quantitatively compared to the MOPITT CO retrievals:

$$x_{ret} = A x + (I - A)x_a.$$

The averaging kernels indicate the sensitivity of the MOPITT measurements to the true CO profile, with the remainder of the information set by the a priori profile. Since the averaging kernels depend on the temperature profile, surface temperature and surface emissivity, they vary with location and time. This version of the MOPITT retrievals are performed on 7 vertical levels (surface, 850, 700, 500, 350, 250, 150 hPa), therefore the absolute values of the averaging kernels are dependent on this retrieval configuration. A single, global a priori profile is used for the version 3 retrievals [Deeter *et al.*, 2003]. Figure 2 shows an



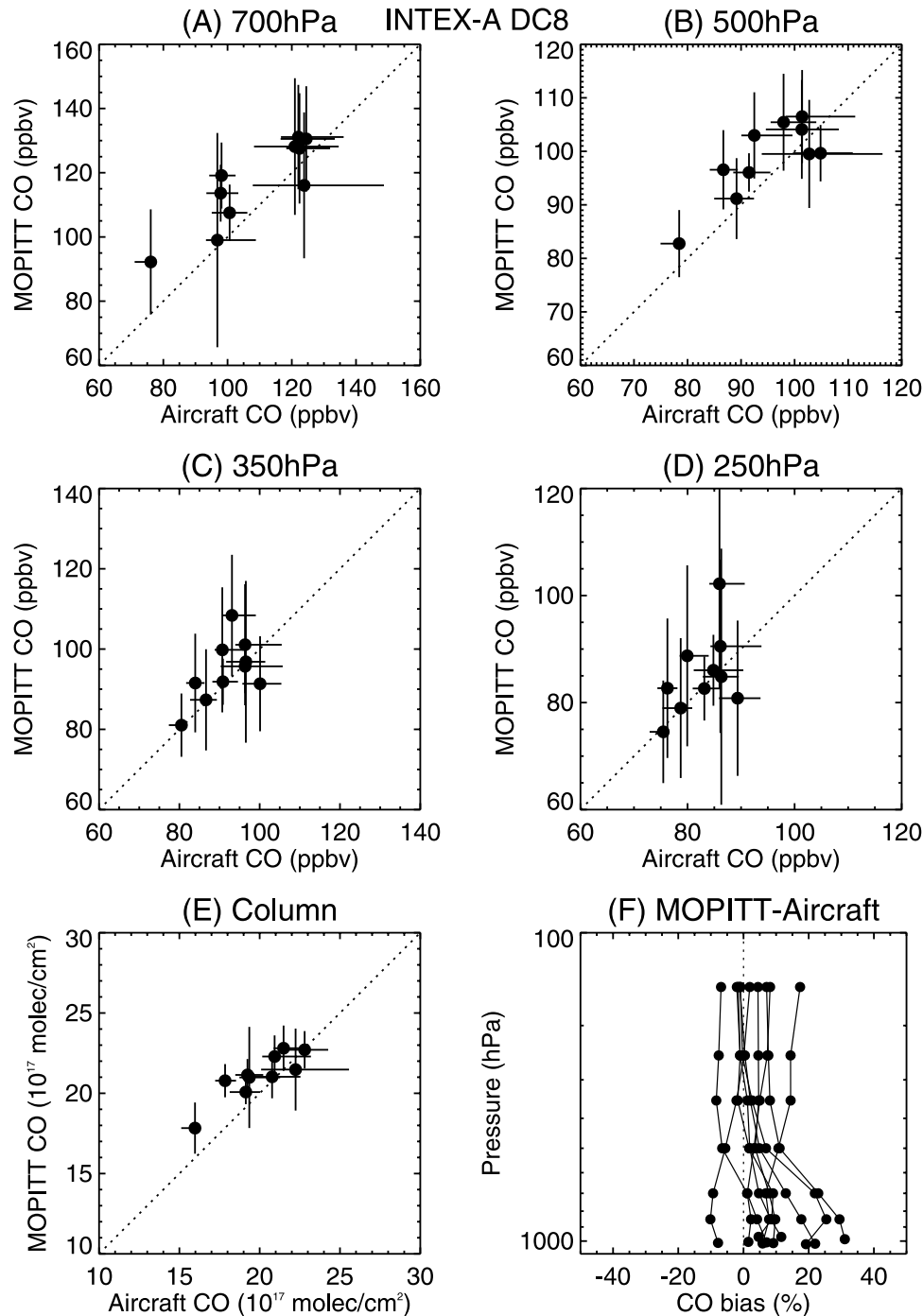
**Figure 2.** Example of comparison of in situ profile to MOPITT retrieval and averaging kernels for one MOPITT pixel (at 35°N, 275°E), from the INTEX-A DC-8 flight on 6 August. (a) Original (small black dots) and vertically binned (large black dots) in situ data, transformed in situ profile with averaging kernels (red asterisk), a priori CO profile (light blue dotted line), and MOPITT profile (dark blue line with error bars indicating the uncertainty in the MOPITT retrieval). (b) MOPITT averaging kernels for each retrieval level. (c) Column averaging kernel, with the CO total column amounts from the MOPITT retrieval and calculated from the in situ profile, using the averaging kernels.

example of the transformation of an in situ profile with the averaging kernels and the a priori (from the INTEX-A flight on 6 August). The original in situ measurements are shown as small dots to illustrate the atmospheric variability resolved at those scales. The large black dots with error bars show the median and quartiles of the in situ data when binned to the 7 MOPITT retrieval levels. Also shown are the averaging kernels for each retrieval level and the total column for this single MOPITT pixel. The averaging kernels shown in Figure 2b show that the MOPITT retrievals are primarily sensitive to CO at altitudes of 700–500 hPa, with some additional information in the upper troposphere. In Figure 2a, it is clear that the fine vertical structure of the in situ measurements cannot be resolved by MOPITT. This vertical sensitivity is primarily dictated by the fairly broad weighting functions and the retrieval requirement of sufficient thermal contrast between the surface and atmosphere, and is shared by other satellite CO measurements, such as those from the Atmospheric Infrared Sounder (AIRS) on board Aqua and the Tropospheric Emission Spectrometer (TES) on board Aura, that also use the thermal infrared CO spectral band. However, once the averaging kernels and a priori profiles have been used to transform the in situ profile, it can be properly compared to the MOPITT retrievals. Figure 2c shows the averaging kernel for the column retrieval, which peaks at about 500 hPa. For this case, the column calculated by transforming the in situ profile with the column averaging kernel is  $21.73 \times 10^{17}$  molecules/cm<sup>2</sup>, agreeing well with the MOPITT column retrieval of  $22.13 \times 10^{17}$ .

[12] Comparisons were made when there were at least 5 MOPITT pixels within 100 km and 4 hours of an in situ profile. Generally each comparison included 10–

50 MOPITT pixels, which is determined by cloud cover, and the location of the in situ profile relative to the MOPITT swath. The in situ profiles were extended to 150 hPa using results from chemistry transport simulations with the Model for Ozone and Related Chemical Tracers (MOZART) for the summer of 2005 presented by Pfister *et al.* [2005], using the technique described by Emmons *et al.* [2004]. The uncertainties introduced through this profile extension are expected to be small [Emmons *et al.*, 2004], particularly since the aircraft profiles used here generally reached to above 350 hPa.

[13] The results of the validation comparisons are shown for each aircraft campaign in Figures 3–5. In Figures 3a–3e, 4a–4e, and 5a–5e, the MOPITT retrievals are plotted against the in situ data transformed by the averaging kernels for the four retrieval levels that contain the most information from the MOPITT measurements (700, 500, 350, 250 hPa) plus the column. Each point in these panels represents the validation for a single in situ profile, showing the median and inner quartile range of the MOPITT pixels in that overpass as vertical error bars. These error bars reflect both the true variability of CO in the atmosphere over 100 km distances, as well as the random errors in the MOPITT retrievals. The horizontal error bars are determined by using the 25th and 75th quartiles of the binned in situ data (discussed above and illustrated in Figure 2), thus representing the variability in CO over fine vertical scales. Figures 3f, 4f, and 5f show the bias (MOPITT minus in situ data) for each comparison (between the transformed in situ data and the MOPITT median) for the full profile. The mean and standard deviation of these biases were determined in absolute mixing ratio, as well as fractional differences, and are given in Table 1. The correlation coefficients for



**Figure 3.** Comparison of MOPITT CO retrievals to the INTEX DC8 in situ profiles that have been transformed by the MOPITT averaging kernels and a priori CO profile. (a–e) Each point represents the mean of all the MOPITT retrievals used in comparison with each aircraft profile plotted against the transformed aircraft profile. See text for explanation of the error bars. (f) Each point of Figures 3a–3e plotted as percent bias ((MOPITT-aircraft)/aircraft).

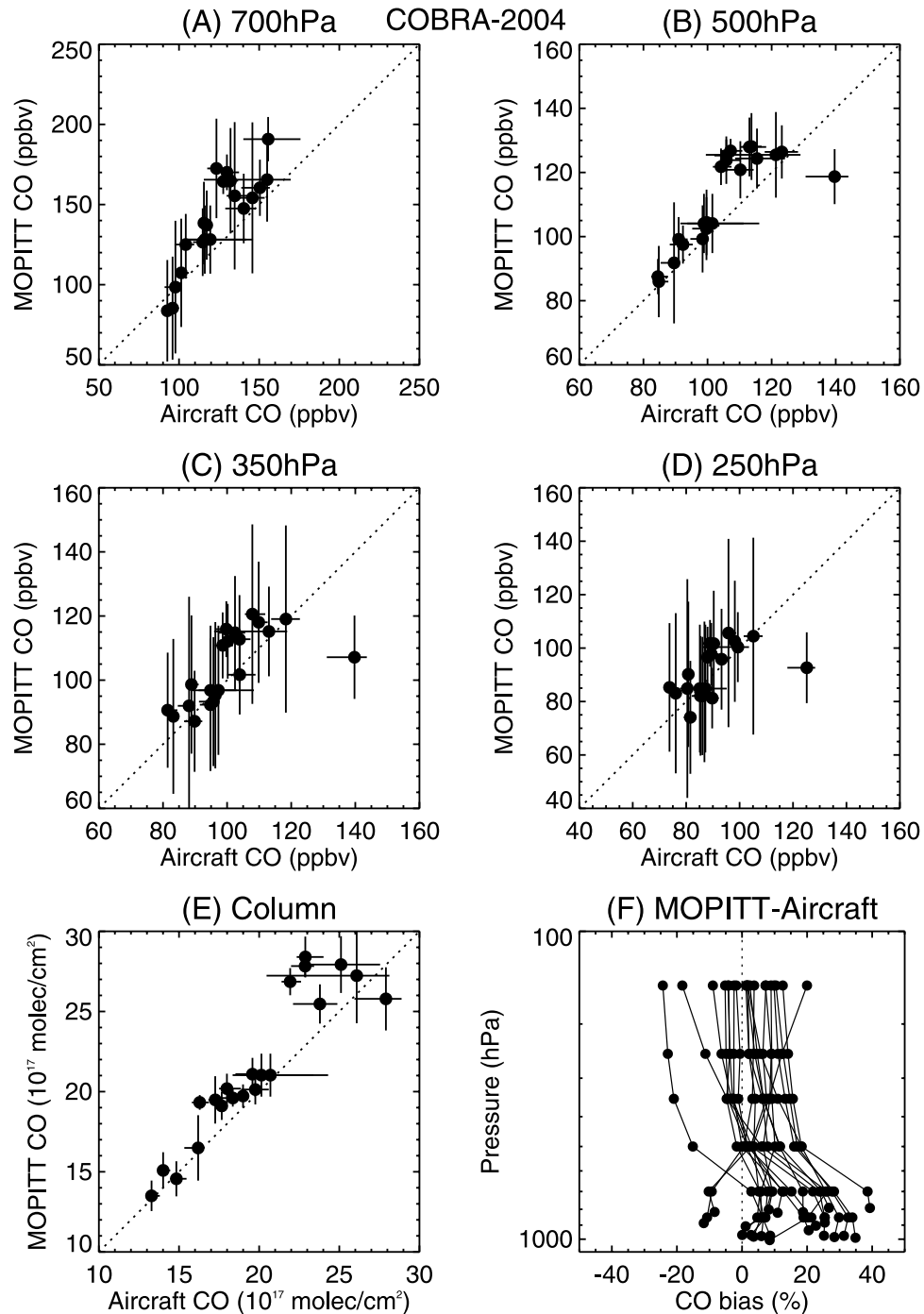
the comparisons shown in Figures 3a–3e, 4a–4e, and 5a–5e are also in Table 1, giving an additional indication of the degree of scatter, or uncertainty, in the validation.

[14] On average, MOPITT shows a positive bias in comparison to the in situ measurements. While there is some variation in the bias values between campaigns, they overlap within their standard deviations. The INTEX-A profiles happened to be made in relatively clean conditions, yet the

biases lie between the results from the other two campaigns which cover more polluted regions. This implies there is no change in bias with CO magnitude, at least in this moderate range (80–200 ppbv at 700 hPa).

[15] The results from these comparisons agree well with the validation results for the vertical profiles sampled by NOAA/ESRL at three North America sites presented by *Emmons et al.* [2004]. For the “phase 2” results presented





**Figure 4.** As in Figure 3 but for the COBRA-2004 flights.

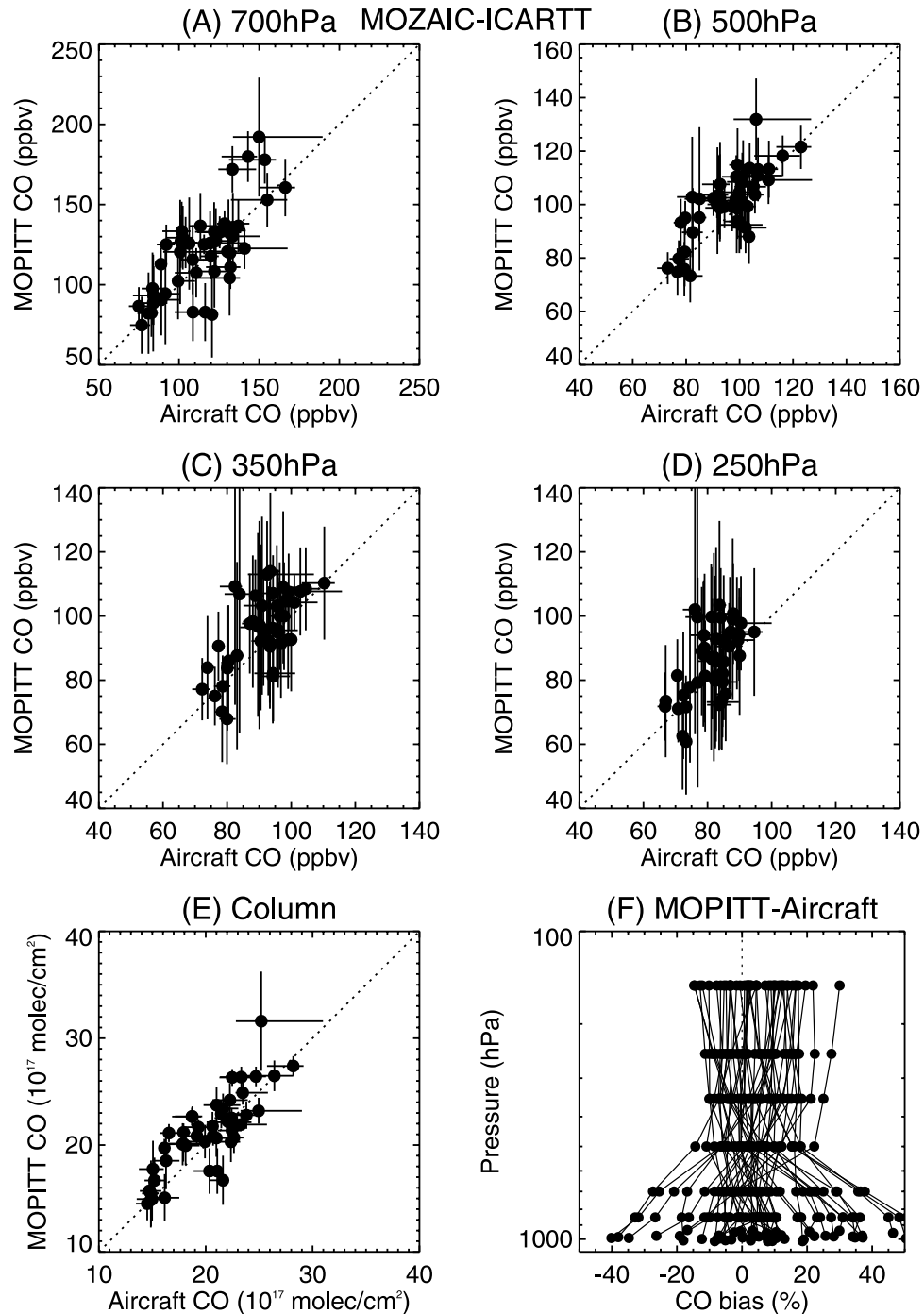
there (August 2001 through December 2002), the bias between MOPITT and the in situ measurements, at 700 hPa was  $16.6 \pm 21.8$  ppbv ( $14.1 \pm 18.5\%$ ) for Carr, Colorado,  $12.8 \pm 7.9$  ppbv ( $10.9 \pm 6.7\%$ ) for Harvard Forest, Massachusetts, and  $8.9 \pm 14.2$  ppbv ( $7.4 \pm 10.2\%$ ) for Poker Flats, Alaska. While the scatter in the validation results both for the NOAA/ESRL measurements and the 2004 campaigns is large, there is an indication that the MOPITT CO retrievals have a slight positive bias, at least over continental regions.

[16] MOPITT CO retrievals are compared to AIRS CO retrievals during INTEX-A in another paper in this issue

[Warner *et al.*, 2007]. MOPITT and AIRS use different types of retrieval algorithms, so care must be taken in comparing the two. When the averaging kernels and a priori profiles of each retrieval are taken into account, MOPITT and AIRS CO agree within an average of 10–15 ppbv [Warner *et al.*, 2007].

#### 4. Conclusions

[17] While the three campaigns show generally similar results, some of the differences in bias and variability can be explained by the differences in the sampling procedures of



**Figure 5.** As in Figure 3 but for the MOZAIC profiles at airports within the ICARTT period and region.

each campaign. The validation results for INTEX show slightly smaller biases and standard deviations, and slightly better correlation coefficients, than the other campaigns. This is likely due to the fact that the profiles were made as spirals and designed to be within 1 hour of the MOPITT overpass, resulting in a higher probability that the DC-8 and MOPITT were sampling the same air masses at all altitudes. Since the COBRA and MOZAIC measurements were not designed to be coordinated with MOPITT overpasses, and the vertical sampling was spread out over longer distances, it is not surprising that the comparisons for those campaigns are more variable. The MOZAIC measurements are also

made in the generally more polluted regions of North America as the commercial aircraft necessarily are landing and taking off from large urban areas. While most of the MOZAIC profiles are sampled away from actual airports, they are in very chemically heterogeneous atmospheric conditions, introducing significant variability in the comparisons with MOPITT. This is the cause of the high variability in the biases shown in Figure 5f in the lower troposphere. The overall biases and standard deviations given in Table 1, however, are not much larger than the INTEX validation because of the larger number of profiles used from MOZAIC.

**Table 1.** Correlation Coefficient (R) and Mean and Standard Deviation of Absolute and Fractional Biases Between MOPITT and In Situ Measurements for Summer 2004 Over North America

Level	R	Absolute Bias <sup>a</sup>	Fractional Bias, %
<i>INTEX-DC8</i>			
700 hPa	0.86	7.4 ± 9.8	7.9 ± 9.7
500 hPa	0.80	2.7 ± 5.6	3.2 ± 5.9
350 hPa	0.66	2.2 ± 5.9	2.6 ± 6.2
250 hPa	0.64	1.9 ± 5.2	2.5 ± 6.2
Column	0.77	1.0 ± 1.4	5.4 ± 7.1
<i>COBRA-2004</i>			
700 hPa	0.86	18.4 ± 15.4	14.4 ± 12.5
500 hPa	0.79	6.1 ± 9.1	5.9 ± 8.0
350 hPa	0.65	2.9 ± 9.8	3.4 ± 8.6
250 hPa	0.57	1.2 ± 9.2	1.9 ± 8.9
Column	0.91	1.5 ± 1.9	7.7 ± 8.3
<i>MOZAIC</i>			
700 hPa	0.72	7.0 ± 17.6	6.6 ± 15.3
500 hPa	0.78	3.0 ± 6.6	3.4 ± 7.1
350 hPa	0.68	3.0 ± 7.9	3.4 ± 8.5
250 hPa	0.63	2.9 ± 7.7	3.5 ± 9.5
Column	0.82	0.9 ± 1.9	5.0 ± 9.4

<sup>a</sup>700, 500, 350, and 250 hPa levels in ppbv; column in 10<sup>18</sup> molecules/cm<sup>2</sup>.

[18] The large variability seen in all cases is also due to the mismatch in scales between the satellite and aircraft measurements. The MOPITT pixels are 22 km by 22 km across, while the aircraft in situ samples are essentially a point. Therefore MOPITT has inherent horizontal averaging that it is impossible to represent with the aircraft measurements. This is not such a problem in remote, uniformly clean regions, but over North America the atmosphere is very likely to have considerable variability and structure in the CO distribution.

[19] The results of these MOPITT validation comparisons with 3 field campaigns during the Summer of 2004 show that the MOPITT CO retrievals over North America have a slight positive bias, which is consistent with previous validation results [Emmons *et al.*, 2004], and is within the MOPITT design criteria for 10% accuracy. Future validation studies will be performed using additional data, including the regular measurements by NOAA/ESRL from small aircraft at a number of sites around the globe, the full MOZAIC data set, and ground-based spectroscopic measurements, for the full MOPITT record (2000 to present). These validation comparisons indicate the continued scientific validity of the MOPITT CO retrievals for model evaluation and quantitative studies of the CO distribution.

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